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13. ABSTRACT (Maximum 200 words) Different field and laboratory methods for determining the hydraulic properties of unsaturated soils were studied. Drying moisture retention curves were measured on undisturbed soil samples with a pressure plate apparatus, and wetting soil moisture retention curves were measured on repacked soil columns via a capillary rise experiment. Saturated hydraulic conductivities were measured in-situ with a Guelph permeameter, and in the laboratory with falling head tests. Finally, an inverse modeling technique was used to analyze transient flow data from in-situ cone permeameter and laboratory multi-step outflow experiments to simultaneously obtain wetting and drying curves for both the moisture retention and the hydraulic conductivity functions. The retention curves obtained from analysis of the cone permeameter data were consistent with results of the multi-step outflow tests and bounded by the capillary and pressure plate test results, as expected. The retention curves derived from cone permeameter data exhibited more curvature than those obtained from the other methods. The curves obtained from multi-step outflow tests exhibited less hysteresis than those derived from cone permeameter tests and were more repeatable than the pressure plate test results.				
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FINAL REPORT
Augmentation Award for Science and Engineering Research Training:
Unsaturated Soil Hydraulic Parameter Studies

Grant Number 36895-EV-AAS
Parent Grant Number DAAH04-95-1-0228

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STATEMENT OF THE PROBLEM STUDIED

This augmentation award was used to support a doctoral candidate in the Department of Civil and Environmental Engineering at the University of South Carolina. The parent grant was the PI's Young Investigator Award (DAAH04-95-1-0228). The augmentation award made it possible for the student to gain valuable field experience while working toward her doctoral degree. With financial support from this award, the student presented a paper at the 1999 annual Soil Science Society of America meeting in Salt Lake City, and the 1999 South Carolina Water and Environment Symposium. She has also been involved in the production of several abstracts and two journal articles.

Knowledge of unsaturated soil hydraulic properties is necessary for predicting the movement of water and water-borne contaminants from surface and near-surface sources to groundwater. Conventional approaches for measuring these hydraulic properties in unsaturated soils are limited to near-surface application and/or require augering a borehole, which may result in contaminated soil being brought to the surface. In addition, most methods are based on steady state flow measurements, which can make testing very time consuming. The parent grant involved investigation of the fundamental relationships between transient flow processes and soil hydraulic properties, and development of a new cone penetrometer method for determining unsaturated soil hydraulic properties from transient flow measurements.

RESEARCH OBJECTIVES

The overall goals of the parent grant were to investigate the fundamental relationships between measurable transient unsaturated flow responses and soil hydraulic parameters, and develop a new method based on transient measurements. Specific objectives of this work included 1) designing a modified cone penetrometer (called a cone permeameter) to inject water into to subsurface and measure pressure head responses, 2) creating an inverse methodology for estimating hydraulic properties of unsaturated soils from cone permeameter data, 3) demonstrating the performance of a prototype via carefully controlled full-scale laboratory tests, and 4) testing the methodology and instrumentation in the field. Results from the parent grant activities were reported in detail in a final report submitted to ARO (Gribb, 1999). An additional

research objective pursued by the doctoral student supported by this augmentation grant involved analysis of a variety of field and laboratory methods for determining unsaturated soil hydraulic properties. The results associated with this research objective are the subject of this report, and a journal article currently under revision (Gribb and Ordway, 2000).

BACKGROUND

The soil-water retention curve, $\theta(h)$, describing the relationship between the water content and the pressure head of an unsaturated soil, and the unsaturated hydraulic conductivity function of the soil, expressed in terms of pressure head or water content, $K(h)$ or $K(\theta)$, may be parameterized using the van Genuchten (1980) equations:

$$\theta_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h|^n)^m}, \quad h < 0$$

$$\theta_e = 1, \quad h \geq 0$$
(1)

$$K(h) = K_s \theta_e^l \left[1 - (1 - \theta_e^{1/m})^m \right]^2 \quad h < 0$$

$$K(h) = K_s, \quad h \geq 0$$
(2)

where θ_e is the effective water content ($L^3 L^{-3}$), θ_r and θ_s are the residual and saturated water contents ($L^3 L^{-3}$) respectively, α (L^{-1}), n and m (m is set equal to $1 - 1/n$ in this work) are empirical fitting parameters (-), K_s is the saturated hydraulic conductivity (LT^{-1}) and l is the pore connectivity parameter (-). The pore connectivity parameter, l , is commonly set equal to 0.5 (Mualem, 1976).

The cone permeameter was designed to obtain estimates of these important hydraulic properties. To perform a test, the cone permeameter is used to inject water into the soil in increasing steps of positive pressure through a screened section. The device also measures movement of the wetting front with tensiometers located above the screen (Figure 1) (Gribb et al., 1998). The parameters describing the $K(h)$ and $\theta(h)$ relationships are estimated by analyzing cumulative inflow volume and pressure head readings using an inverse solution technique. To accomplish the inversion, a cone permeameter test is numerically simulated with the radially symmetric form of the Richards equation with parameterized functions of $K(h)$ and $\theta(h)$ (Equations 1 and 2). Then an objective function expressing the differences between flow responses measured with the cone permeameter, and those predicted using a numerical model with parameterized soil hydraulic property inputs, is minimized using the Levenberg-Marquardt method (Marquardt, 1963). The minimization yields the parameters most likely to be correct for the soil.

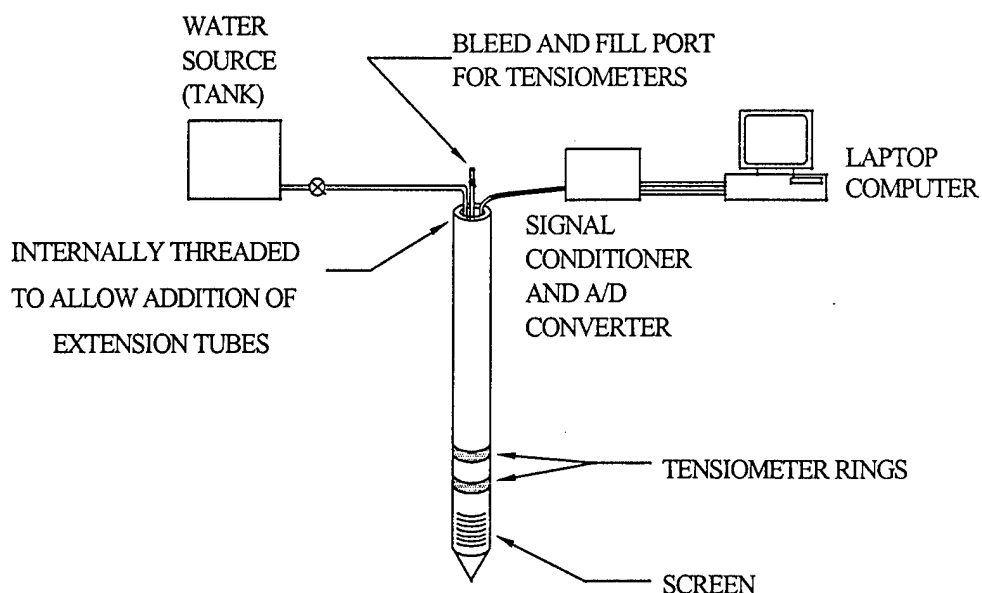


Figure 1. Cone permeameter schematic. Water is supplied to the soil through the screen while pore water pressure responses are measured at the tensiometer assemblies located above the screened section. The volumetric inflow volume is also recorded continuously during testing.

SUMMARY OF THE MOST IMPORTANT RESULTS

The parent grant objectives were met via a program of numerical and experimental studies. Numerical studies were undertaken to investigate the effects of varying hydraulic soil properties and test conditions on observed flow responses. A fully functional prototype cone permeameter and data acquisition system were designed and fabricated. Full-scale soil tank experiments were performed to assess the validity of the numerical model predictions and the applicability and ease of use of the prototype in sandy soil (Gribb et al., 1998; Kodesova et al., 1998a,b, 1999a; Šimůnek et al., 1999) (Figure 2). Finally, a field demonstration of the prototype was completed (Kodesova et al., 1999b). Full details are given in the final report for the parent grant (Gribb, 1999).

The results of augmentation grant activities for the past year involve a study of different test methods used to obtain unsaturated hydraulic property information at three field sites. At each site, four Guelph permeameter tests were conducted at a depth of 30 cm on the corners of a 100 cm square to determine saturated hydraulic conductivities. Cone permeameter tests were run at the same depth at points equidistant from the Guelph permeameter tests to obtain information about the wetting and drying retention and hydraulic conductivity curves. Following cone testing, undisturbed soil samples were taken adjacent to the tensiometer rings on the cone permeameter, and grab samples were taken immediately after undisturbed samples were removed. Kodesova et al. (1999) give full details of the field program.

The undisturbed samples were subjected to pressure plate tests to determine the drying retention curves, multi-step outflow tests were used to determine the wetting and drying retention curves, and falling head tests were used to determine saturated hydraulic conductivity values. Repacked columns were subjected to capillary rise experiments to determine the wetting

retention curve for the soil.

Retention curves for five cone permeameter tests and representative results of the capillary rise, pressure plate and multi-step outflow tests for one test site are shown in Figure 2. The retention curves obtained from analysis of the cone permeameter data were consistent with results of the multi-step outflow tests and bounded by the capillary and pressure plate test results, as expected. The results of the several cone tests show good reproducibility. The retention curves derived from cone permeameter data exhibited more curvature than those from the other methods. The curves obtained from multi-step outflow tests exhibited less hysteresis than those derived from cone permeameter tests and were more repeatable than the pressure plate test results. The drying curves obtained from the pressure plate tests suggest that the investigated soils had greater water retention ability than the curves predicted by the other methods. This was likely due to difficulties in maintaining the hydraulic connection between the sample and the porous plate at the higher suction levels. The retention curves obtained from capillary rise tests suggested that the soil had less water retention ability than the curves obtained from other methods, but these results may not accurately reflect the in-situ behavior since repacked samples were used.

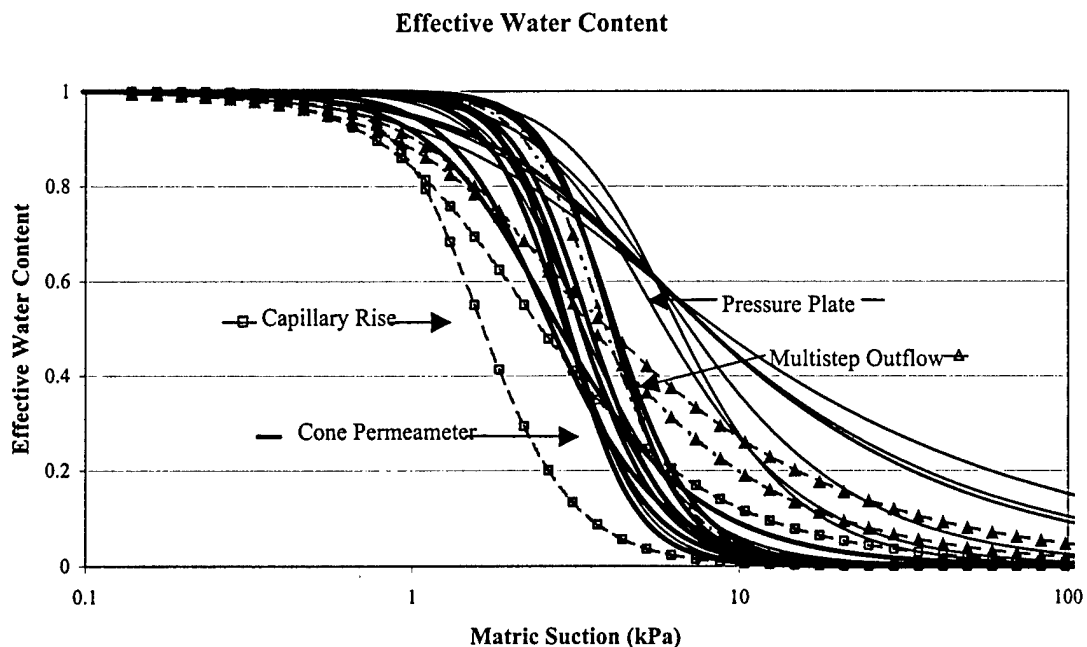


Figure 2. Comparison of soil-water retention curves for the various methods used at a field site located in sandy, coastal plain deposits. Note that the cone permeameter curves include wetting and drying scanning curves, as do the multi-step outflow results. Capillary rise tests yield wetting curves while pressure plate tests yield drying curves.

Excellent agreement was found between the values of saturated hydraulic conductivity obtained from the various methods, as shown in Figure 3. Saturated hydraulic conductivity values from cone permeameter tests ranged between 0.0011 and 0.004 cm/sec, which compared very well with results of laboratory falling head test results that ranged from 0.0013 to 0.0044 cm/sec, multi-step outflow test results that ranged from 0.0012 to 0.0027 cm/sec, and Guelph permeameter results that ranged from 0.0023 to 0.0035 cm/sec.

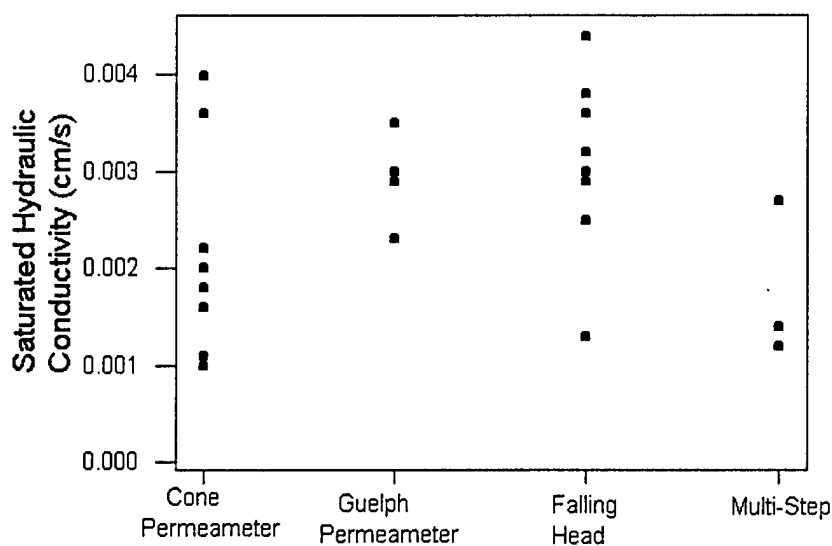


Figure 3. Saturated hydraulic conductivity values obtained from laboratory and field tests for a single study site.

The augmentation grant research activities provided important information about the relative reproducibility and performance of various standard test methods for determining unsaturated soil properties. In addition, the performance of the cone permeameter method was further validated and shown to provide consistent results under field conditions in sandy soils. The information gained on unsaturated flow processes through this work and the parent grant activities have provided the basis for future work with other soil types, and investigations into the effects of soil anisotropy and disturbance due to cone penetration.

ARMY RELEVANCE

The products of the parent and augmentation grants have shown the potential of a new cone penetrometer based method for enhancing the Army's ability to characterize and remediate contaminated sites. When this technology fully developed, it will have numerous advantages over existing methods for soil hydraulic property measurement. As with other cone penetrometer

tools, the cone permeameter is minimally intrusive and does not result in the removal of potentially contaminated materials. This feature safeguards the welfare of operating crews and reduces site investigation costs. The cone penetrometer method is applicable to depths of 30 m or more below ground surface depending on soil resistance to penetration. Since the analysis is based on transient flow data, time and water requirements are minimized. Finally, the inverse solution approach makes it possible to simultaneously determine the soil-moisture retention and hydraulic conductivity curves in unsaturated soils from short-term test data, something not currently possible with other in-situ methods.

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PARTICIPATING SCIENTIFIC PERSONNEL

Sondra Ordway, doctoral candidate, degree expected Aug. 2000.

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